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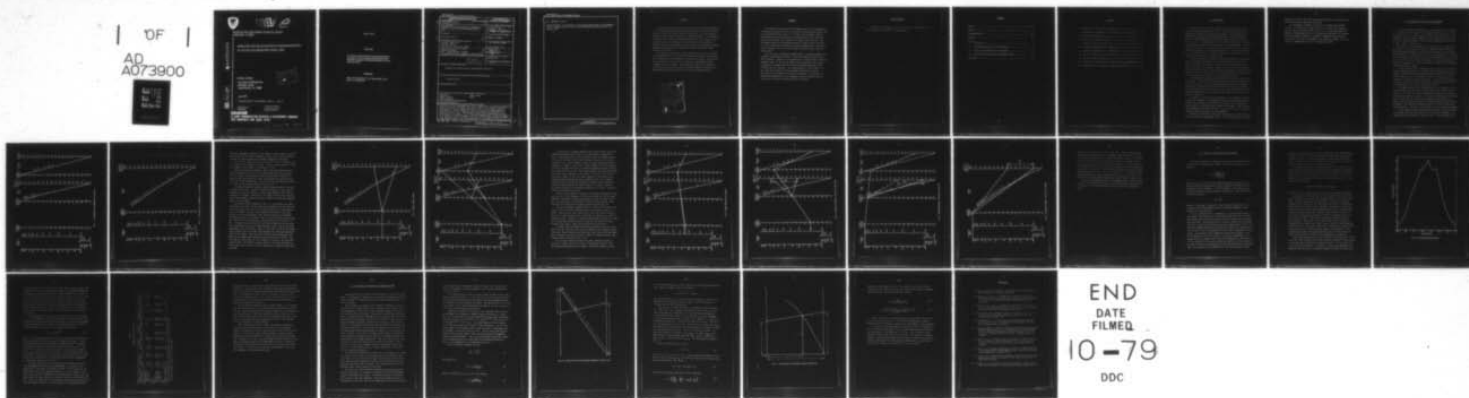
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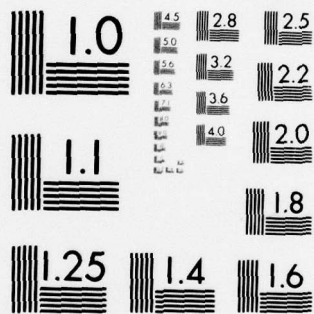
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CORADCOM-77-0142-1

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NOMOGRAMS FOR THE CALCULATION OF PROPAGATION EFFECTS
ON TACTICAL MILLIMETER-WAVE RADIO LINKS

William Sollfrey
THE RAND CORPORATION
1700 Main Street
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June 1979

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20. ABSTRACT (Cont'd)

worked examples. By following the techniques demonstrated in the examples, the user should be able to solve link performance problems speedily and simply. (JDD)

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PREFACE

This Rand Note on aids for the calculation of propagation effects on tactical millimeter-wave radio links was prepared for the U.S. Army as part of a study entitled "Worldwide Performance of Tactical Millimeter-Wave Radio Links," Contract No. DAAB07-77-C-0142. It represents an application of results obtained earlier under this contract. The contracting officer's technical representative on the contract is Emanuel Fliegler (DRSEL-NL-RM-1) of the Millimeter Wave Project Office, Communications Research and Development Command (CORADCOM) at Fort Monmouth, New Jersey.

The nomograms--calculation aids--presented here should be useful to designers and users of tactical millimeter-wave links. They permit the determination of attenuation, rain losses, overshoot effects, and other propagation values simply by placing a straightedge between columnar scales on a graph. This material should be of interest to the military services and to other government agencies interested in employing millimeter-wave radios for short-haul communications.

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SUMMARY

This Rand Note describes the development and use of nomograms for calculating propagation effects on tactical millimeter-wave radio links. In the millimeter-wave band (35 to 75 GHz), the principal causes of attenuation are oxygen absorption, which depends on radio frequency, and rain scattering, which depends on frequency and rain rate. The nomograms display these dependencies and the range equation, and may be used to calculate communication system performance as a function of range, frequency, and rain rate by simply drawing straight lines between scales.

The use of the nomograms is demonstrated by several examples, including a system margin problem, a rain onset problem, and two overshoot problems. Because of the adaptation to tactical links, which are generally short (a few km) and remain near the ground, line of sight propagation is assumed and the effects of antenna height and earth curvature are not included. All calculations are for sea level, but for these short paths the results remain valid below 3 km elevation, which should cover almost all tactical situations. By following the techniques demonstrated in the examples, the user should be able to solve link performance problems speedily and simply.

ACKNOWLEDGMENTS

The author is indebted to J. R. Clark and S. J. Dudzinsky, Jr., who suggested this subject for investigation.

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I. INTRODUCTION

The U.S. Army is developing millimeter-wave radio equipment for use on short-haul communications links. The Rand Corporation, while conducting a study on the general performance of such links, made extensive calculations on link performance under various conditions. There are so many parameters that the presentation could not hope to be exhaustive. It became clear that it would be very useful to develop some calculation aids which would simplify the investigations. We considered the design of a slide rule, but this proved to be too complex. Nomograms turned out to be simple and practical. This Note describes their development and use. Copies suitable for reproduction are contained in a flap on the inside back cover.

Problems suitable for analysis with these nomograms involve propagation at various frequencies in the millimeter-wave band (35 to 75 GHz). The principal causes of attenuation are oxygen absorption and rain scattering. The nomograms present the oxygen attenuation dependence on frequency and the rain attenuation dependence on frequency and rainfall rate. The range equation is used to determine communication system performance as a function of attenuation and range.

The nomograms are adapted to millimeter-wave tactical communications links. Such paths are generally short (a few km) and remain near the ground surface. Line of sight propagation is assumed throughout, and effects of antenna height and earth curvature are not included. All calculations are for sea level, but for these short paths there are no major changes below 3 km elevation, which should cover almost all tactical situations.

In Section II we define the quantities to be calculated, and then present the nomograms. As examples, we work a system margin problem, a rain onset problem, and two overshoot problems, all of which are solved simply by drawing straight lines on the graphs. These illustrative examples should enable the user to see how to solve his link performance problems speedily with the nomograms.

Section III derives the equations, and Section IV demonstrates how they are reduced to nomographic form. If the reader wishes to include

propagation effects other than those presented here, this section will provide him with the necessary materials.

The nomographic technique of this Note is simple and straightforward. An alternative procedure would be to employ the computing power of modern high-speed hand calculators. A recent Rand Report⁽¹⁾ provides 23 programs written for the Hewlett-Packard HP-67/97 programmable calculators, reduces the programs to magnetic cards, and describes how to develop new programs. The interested reader can easily reduce the nomographic results to program strip form.

II. DESCRIPTION AND USE OF THE NOMOGRAMS

We have developed two nomograms, one corresponding to propagation in dry weather, which includes only oxygen attenuation, and the other to propagation in wet weather, which includes both oxygen and rain attenuation. The dry weather nomogram is an expanded version of a part of the wet weather nomogram. The wet and dry nomograms are depicted in Figs. 1 and 2, respectively.

The scales of the nomograms and the relations they represent are as follows. The two scales at the left, labeled Frequency (GHz) and Oxygen Attenuation (dB/km), establish the functional relation between these quantities, as determined by theory and experiment. The folding of the frequency scale depicts how there are several values of frequency in the 50 to 70 GHz band which correspond to the same attenuation. To find the attenuation at a specific frequency, simply draw a horizontal line connecting the scales.

The two vertical and one diagonal scales at the right of the wet weather nomogram represent the relation among path-averaged Rain Rate (mm/hr), Frequency (GHz), and Rain Attenuation (dB/km). The range of the rain-rate scale, 0 to 20 mm/hr, covers over 99.8 percent of all rainfalls in the United States and Europe. To find the attenuation at a specified frequency and rain rate, draw a straight line connecting them and extend it to the rain attenuation scale.

The middle portion of the nomogram relates the combined rain and oxygen attenuation, the range, and the signal level relative to the level at 1 km. This level ratio compares the signal at an arbitrary range to the signal at a range of 1 km, thereby avoiding consideration of the details of particular systems (power, antenna gain, etc.). These scales include the effects of attenuation and of inverse square spreading. The combined attenuation scale is the sum of oxygen and rain attenuation. The use of these scales is best described by example.

The dry weather nomogram includes the Frequency, Oxygen Attenuation, Range, and Path Loss scales of the wet weather nomogram. The spacing has been increased to improve clarity. This nomogram can be

Fig. 1 — Nomogram for propagation during rain

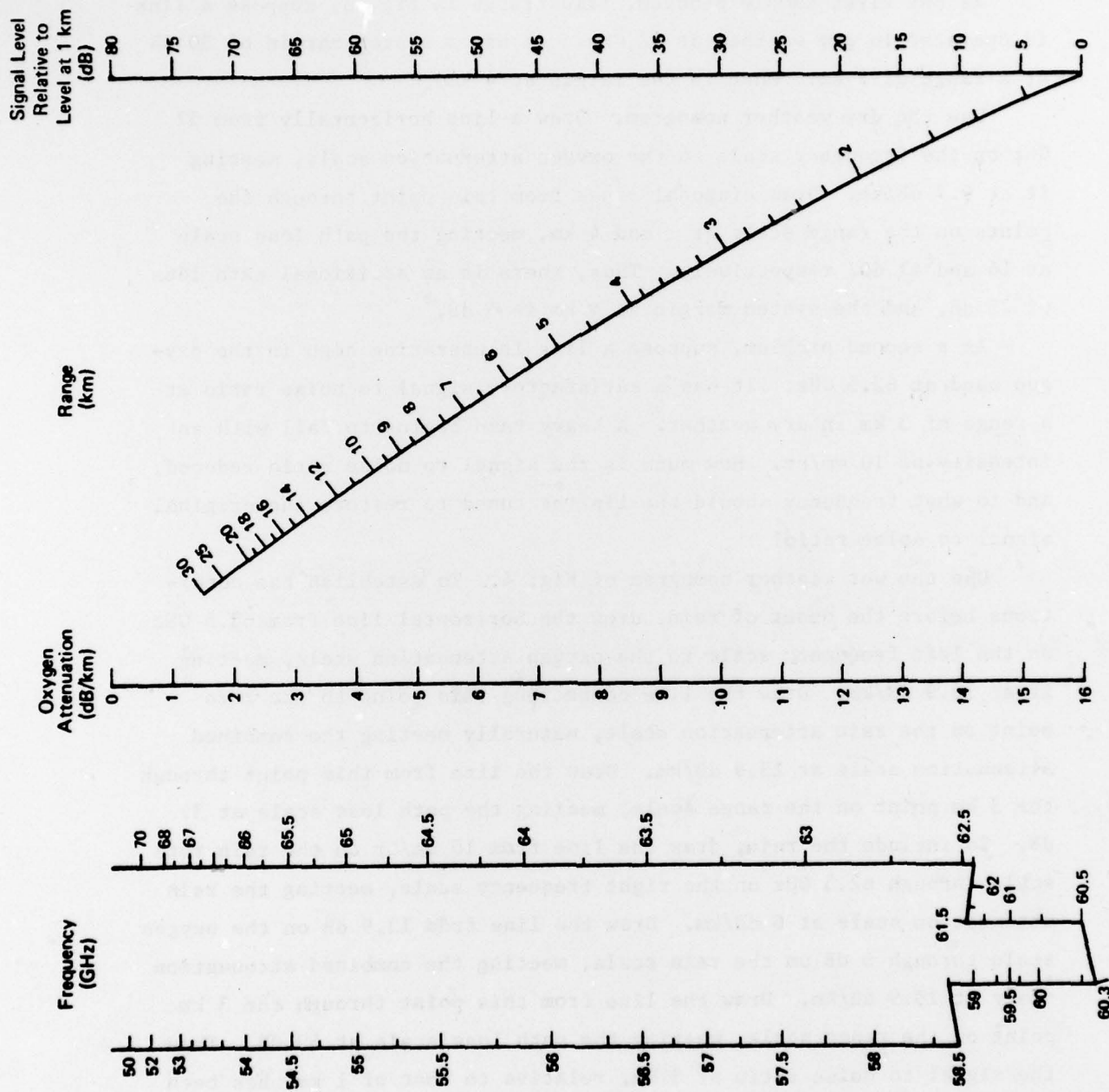


Fig. 2 — Nomogram for propagation in dry weather

used for propagation problems in the absence of rain, which is over 90 percent of the time almost everywhere, except in the wetter tropical regions and some locations with peculiar geographic conditions.

As our first sample problem, illustrated in Fig. 3, suppose a link is operated in dry weather at 57 GHz. It has a system margin of 30 dB at a range of 2 km. What is the margin at 4 km?

Use the dry weather nomogram. Draw a line horizontally from 57 GHz on the frequency scale to the oxygen attenuation scale, meeting it at 9.7 dB/km. Draw diagonal lines from this point through the points on the range scale at 2 and 4 km, meeting the path loss scale at 16 and 41 dB, respectively. Thus, there is an additional path loss of 25 dB, and the system margin at 4 km is 5 dB.

As a second problem, suppose a link is operating high in the oxygen band at 62.5 GHz. It has a satisfactory signal to noise ratio at a range of 3 km in dry weather. A heavy rain begins to fall with an intensity of 10 mm/hr. How much is the signal to noise ratio reduced, and to what frequency should the link be tuned to restore the original signal to noise ratio?

Use the wet weather nomogram of Fig. 4. To establish the conditions before the onset of rain, draw the horizontal line from 62.5 GHz on the left frequency scale to the oxygen attenuation scale, meeting it at 13.9 dB/km. Draw the line connecting this point to the zero point on the rain attenuation scale, naturally meeting the combined attenuation scale at 13.9 dB/km. Draw the line from this point through the 3 km point on the range scale, meeting the path loss scale at 37 dB. To include the rain, draw the line from 10 mm/hr on the rain rate scale through 62.5 GHz on the right frequency scale, meeting the rain attenuation scale at 6 dB/km. Draw the line from 13.9 dB on the oxygen scale through 6 dB on the rain scale, meeting the combined attenuation scale at 19.9 dB/km. Draw the line from this point through the 3 km point on the range scale, meeting the path loss scale at 49 dB. Thus the signal to noise ratio at 3 km, relative to that of 1 km, has been reduced 12 dB. The signal to noise ratio at 1 km itself has been reduced 6 dB by the rain, so the total reduction in signal to noise ratio is 18 dB.

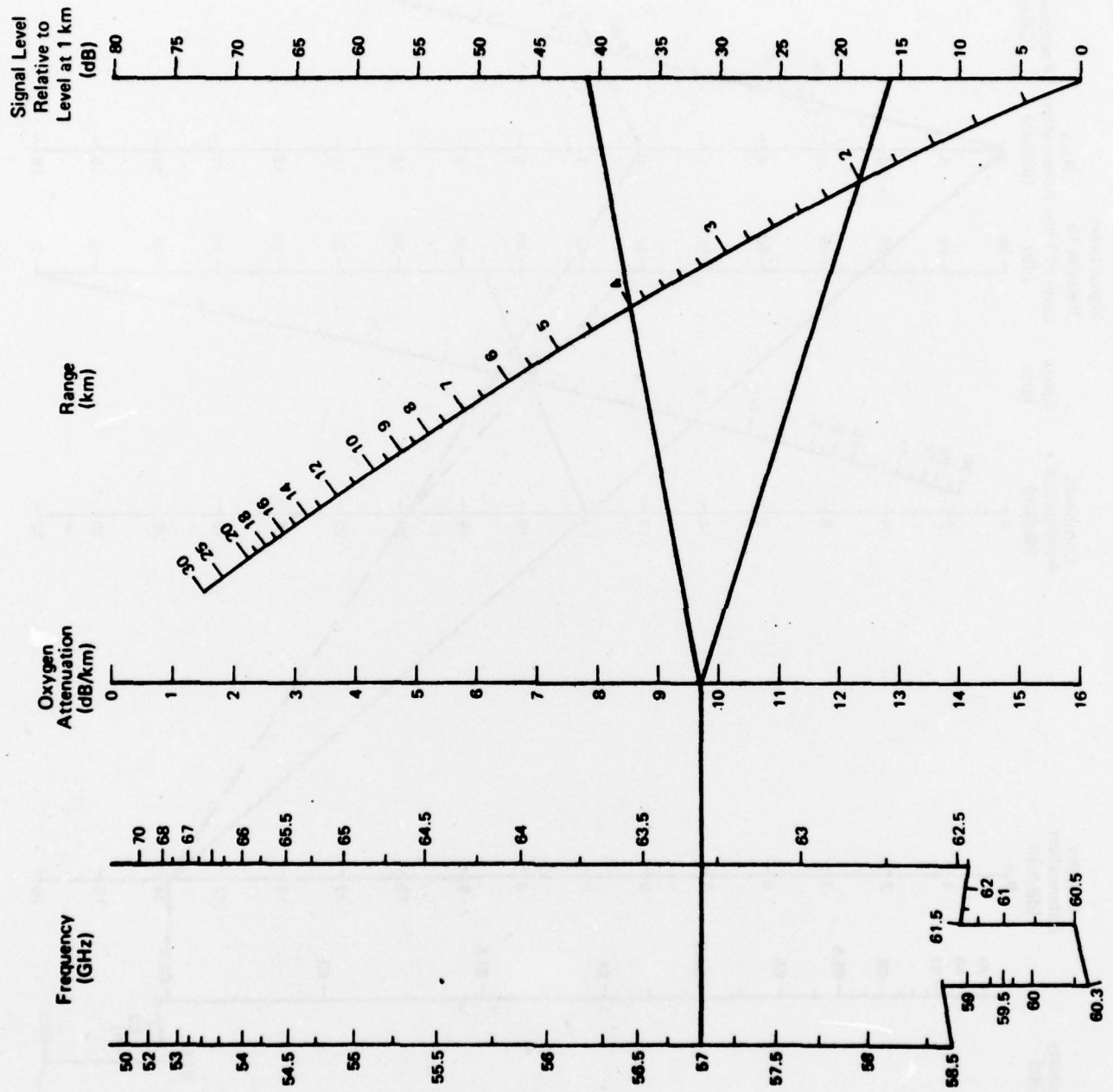


Fig. 3 — System margin problem

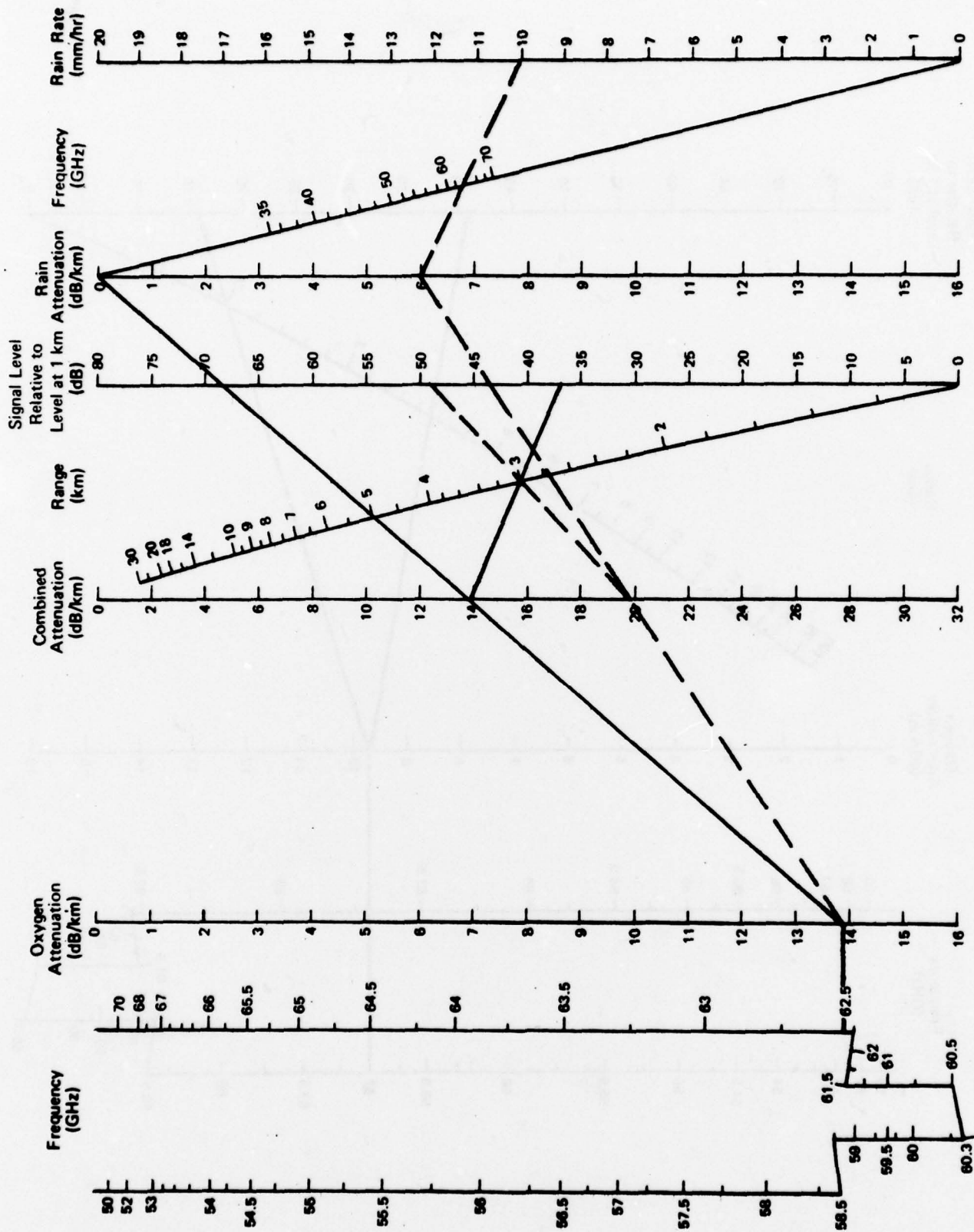


Fig. 4 — Onset of rain signal reduction

To restore the original signal to noise ratio we must return the combined attenuation to 13.9 dB. This calculation is depicted in Fig. 5. We observe that in this frequency region the oxygen attenuation varies much more rapidly with frequency than does the rain attenuation. As a first estimate, assume the rain attenuation remains constant at 6 dB/km. Draw the line from 6 dB/km on the rain attenuation scale through 13.9 dB on the combined attenuation scale, meeting the oxygen scale at 7.9 dB. Draw the horizontal line back to the left frequency scale, meeting it at 63.7 GHz. To correct this, draw the line from 10 mm/hr on the rain scale through 63.7 GHz on the right frequency scale, meeting the rain attenuation scale at 6.2 dB/km. Draw the line from this point through 13.9 dB/km on the combined attenuation scale, meeting the oxygen scale at 7.7 dB/km. Draw the horizontal line and get a frequency reading of 63.75 GHz. Clearly no further correction is required.

As our third problem, we consider an overshoot calculation. Suppose we have a link working at 63 GHz with a range of 3 km in 5 mm/hr rainfall. An enemy is further away along the line of sight, and he has a receiver which is 30 dB better than our field receiver. How near does the enemy have to approach before he can detect us?

Use the wet weather nomogram of Fig. 6. Draw the horizontal line from 63 GHz on the left frequency scale to the oxygen scale at 11.3 dB/km. Draw the line from 5 mm/hr on the rain rate scale through 63 GHz on the right frequency scale, obtaining 3.2 dB/km on the rain attenuation scale. Connect the separate attenuations, getting 14.5 dB/km on the combined attenuation scale. Draw the line from this point through 3 km, giving a path loss of 38 dB for our receiver.

An enemy, with an assumed 30 dB better receiver, can take a path loss of 68 dB. Draw the line from 14.5 dB/km on the combined attenuation scale through 68 dB on the path loss scale, and we find the enemy has to approach to within 4.8 km to receive our signal with the same signal to noise ratio we have at 3 km.

As our final problem, consider the same overshoot problem at 40 GHz in 5 mm/hr rain (Fig. 7) and in dry weather (Fig. 8). The dry weather attenuation is 0.15 dB/km. (This value cannot be shown

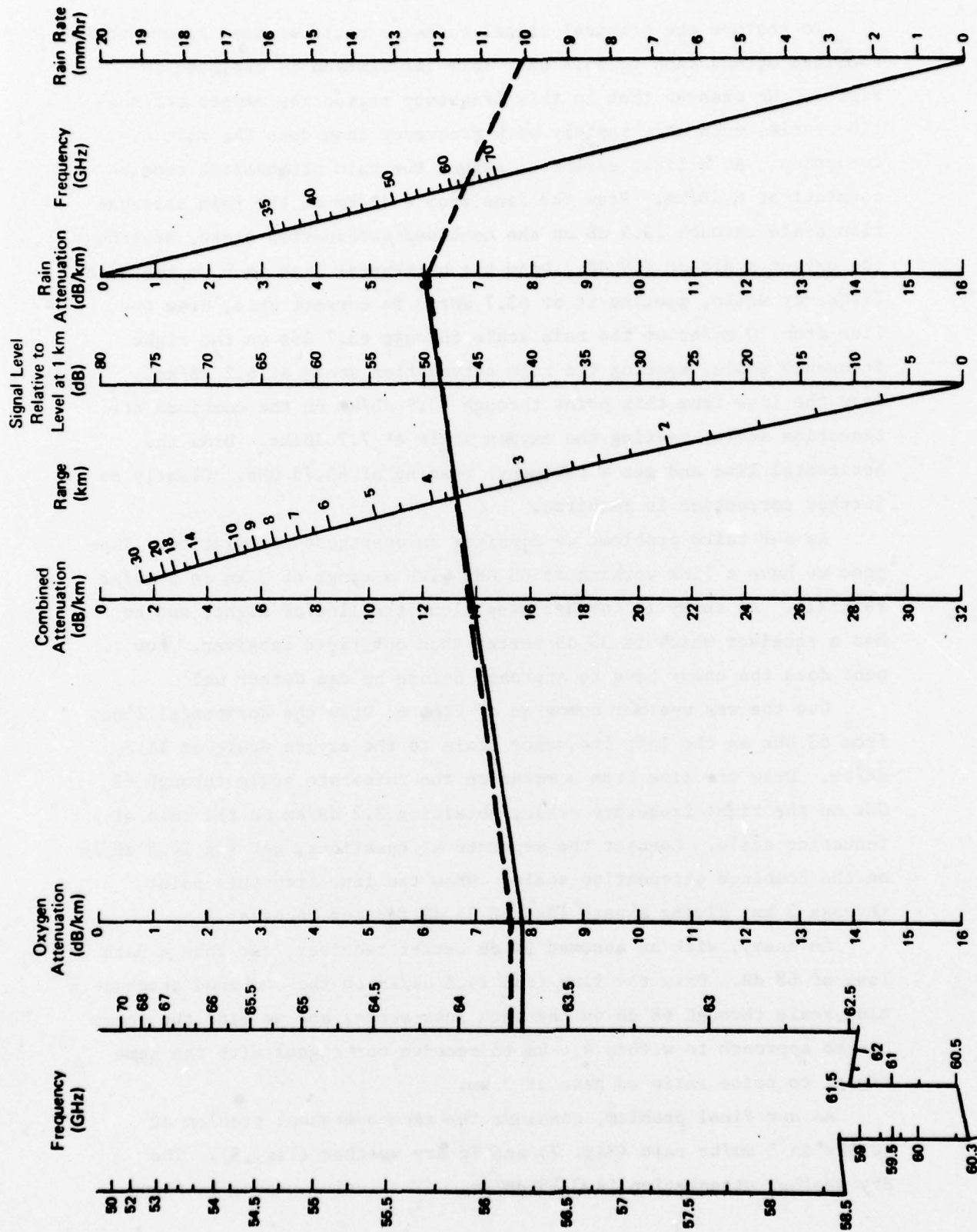


Fig. 5 — Signal restoration by retuning

Fig. 6 — Overshoot problem — 63 GHz, 5 mm/hr rain

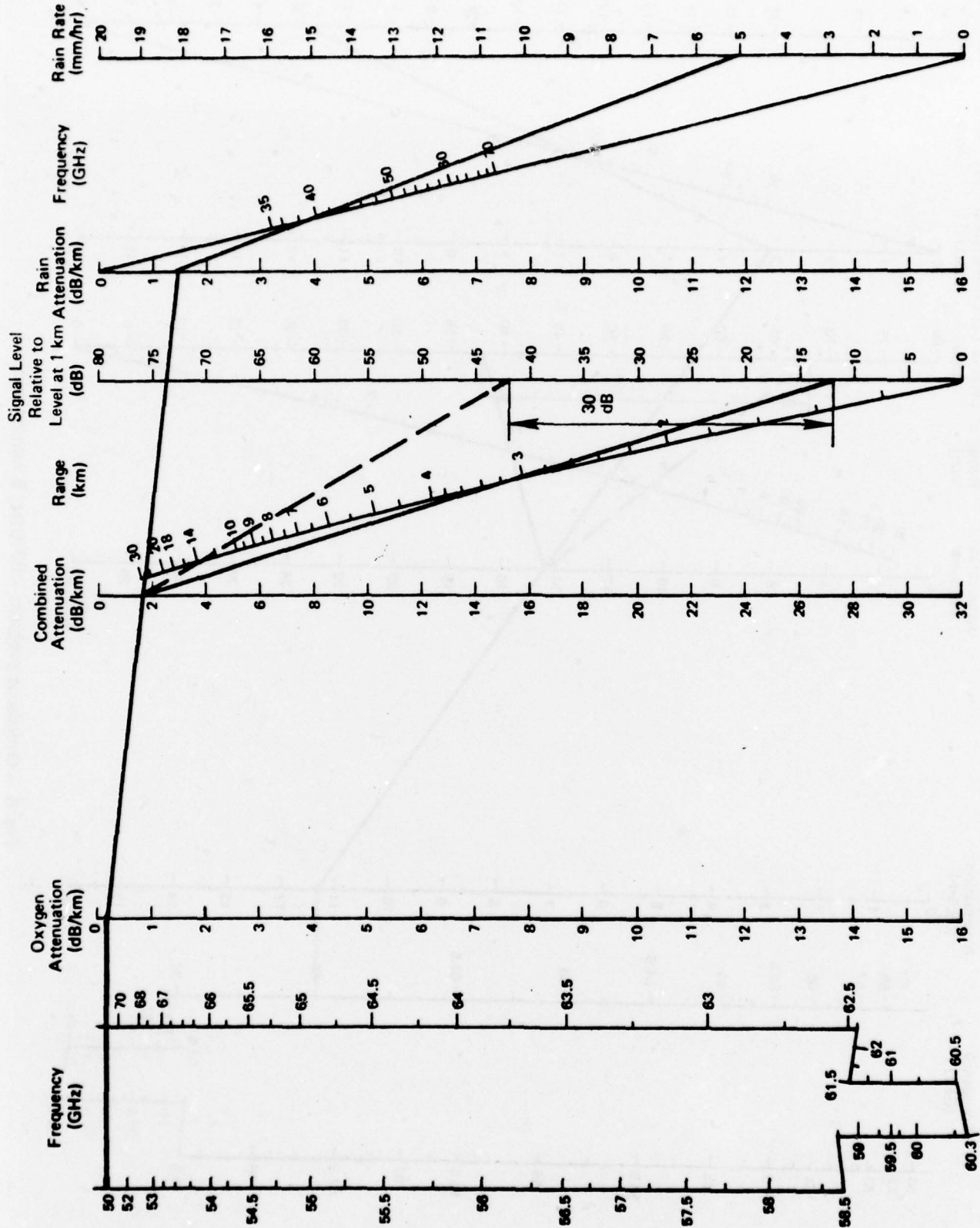


Fig. 7 — Overshoot problem — 40 GHz, 5 mm/hr rain

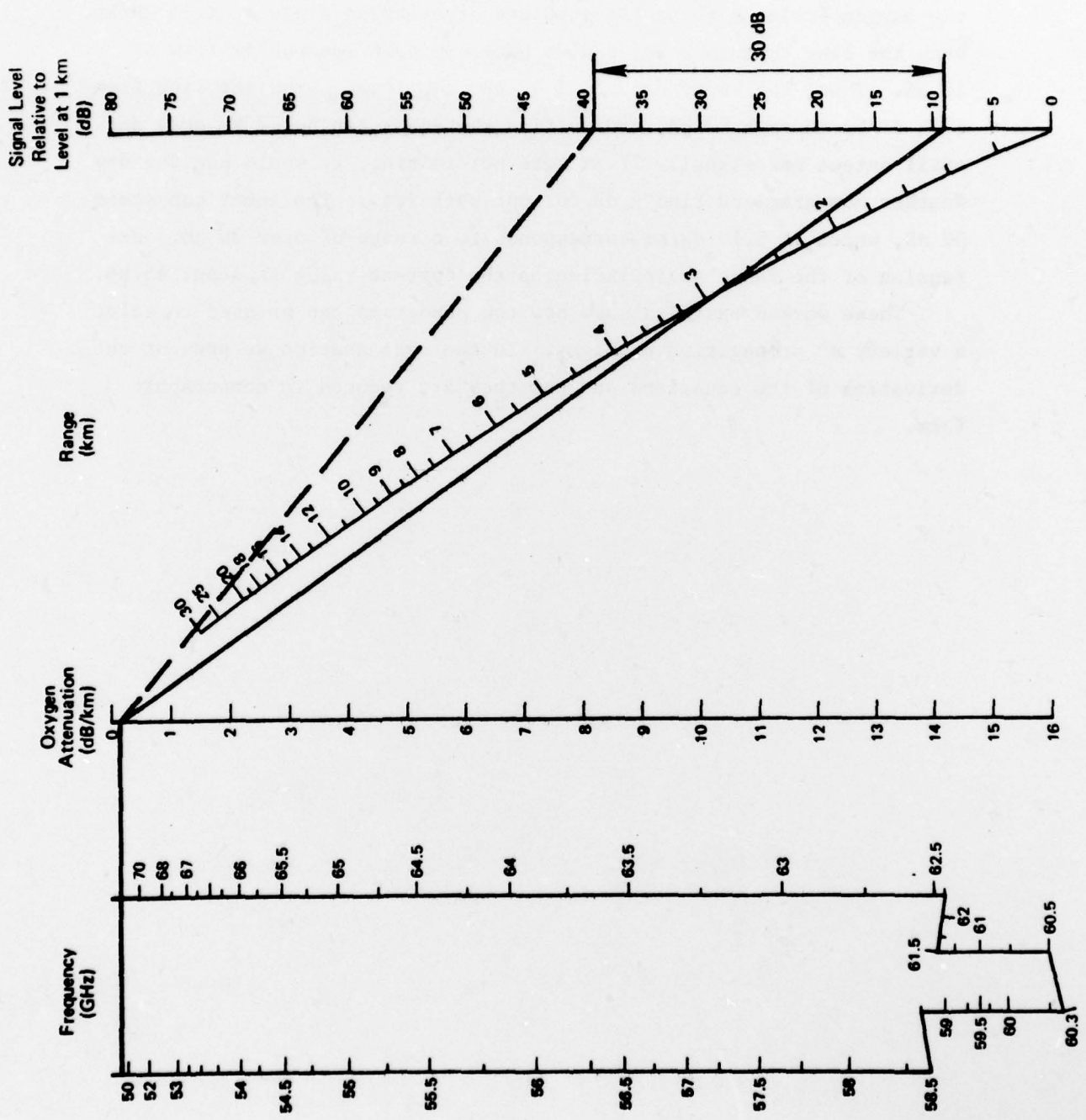


Fig. 8 — Overshoot problem - 40 GHz, dry weather

clearly on the nomogram.) Draw the line from 5 mm/hr through 40 GHz, obtaining a rain attenuation of 1.6 dB/km. Draw the line to 0.15 on the oxygen scale, meeting the combined attenuation scale at 1.75 dB/km. Draw the line through 3 km, and we have our path loss below 1 km of 12 dB. Thus, the enemy can stand 42 dB path loss. Draw the line from 1.75 dB/km through 42 dB, and we find the enemy can be 12 km away and still detect our signal. If it were not raining, we would use the dry weather nomogram and find 9 dB for our path loss. The enemy can stand 39 dB, which at 0.15 dB/km corresponds to a range of over 30 km. Extension of the range scale indicates the correct value is about 45 km.

These worked examples show how the nomograms can be used to solve a variety of propagation problems. In the next section we present the derivation of the equations and how they are reduced to nomographic form.

III. THEORY OF MILLIMETER-WAVE ATTENUATION

The basic equations for communications link performance are found in any text on communications systems. We have for the power at the receiver:

$$P_R = \frac{P_T A_T A_R \eta_T \eta_R}{\lambda^2 R^2 L_T L_R L_P} \quad (1)$$

where P_T , A_T , η_T , and L_T are the transmitter power, antenna area, antenna efficiency, and microwave losses, subscript R denotes the same quantities at the receiver, λ is the wavelength, R the range, and L_P the additional path losses produced by attenuation. The noise in the receiver is given by

$$N_R = kTB \quad (2)$$

where k is Boltzmann's constant, T the effective temperature of the receiver, and B the bandwidth required to transmit whatever signal waveform is being employed.

We are concerned with the dependence of the system performance on range and on the frequency in the millimeter-wave band (35 to 75 GHz). The antenna efficiency and microwave losses are substantially constant over this band. The antenna areas are usually reduced with increasing frequency, essentially maintaining constant antenna gain ($\sim A/\lambda^2$). The receiver bandwidth depends on the data rate required for system operation, which in turn is determined by tactics and is independent of frequency. The receiver noise temperature varies with frequency. Over the entire band, the total variation of the noise temperature for a single device is perhaps 2 dB. The noise temperature is also affected by rain intensity, but since the noise temperature of devices likely to be used for tactical communications in the next twenty years is already high, the additional noise generated by rain only produces a slight

increase in noise temperature. We will regard the noise temperature as constant, subject to the discussion above. Further investigations are contained in Ref. 2. With all these factors determined, the system power is then chosen to provide satisfactory operation at some selected range, frequency, and choice of weather conditions.

The standard measure of system performance is the signal to noise ratio. Most of the factors in this ratio are independent of frequency and range. To eliminate these factors, we shall normalize by referencing the signal to noise ratio to its value at a range of 1 km. This normalized ratio defines the effective path loss (PL) below 1 km, which we express in decibels as

$$PL(\text{dB}) = A(f)(R-1) + 20 \log_{10} R \quad (3)$$

where $A(f)$ is the attenuation in dB/km and is a function of frequency.

Attenuation in the atmosphere in the millimeter wave band is produced by oxygen, water vapor, and condensed water in the form of rain, hail, or snow. Absorption by water vapor is caused by a molecular resonance at 22 GHz, and is not significant in the 35 to 75 GHz band. Snow and hail also do not produce important attenuation in this band. We do not expect tactical communications paths to pass through clouds. Typical fogs have liquid water content on the order of 0.25 g/m^3 or less, which produces an attenuation of about 0.1 dB/km at 35 GHz, or 0.6 dB/km at 75 GHz,⁽³⁾ well below the attenuation produced by a 1 mm/hr rainfall. Much denser fogs (1 g/m^3) can produce attenuation comparable to a 5 mm/hr rain. These occur so rarely in most locations that we shall not investigate them further. From these considerations, we see that the only really important causes of attenuation in the millimeter-wave band are oxygen absorption and rain scattering, and these are the effects included in the nomographic presentation.

The oxygen molecule has a broad spectrum of rotation lines centered on 60 GHz. The attenuation has been carefully measured,⁽⁴⁾ and a graph of the sea level absorption is presented in Fig. 9. We see from this curve that the attenuation is 1 dB/km at 53 GHz, rises smoothly to 14 dB/km at 58.5 GHz, varies irregularly between 58.5 and 62.5 GHz with a

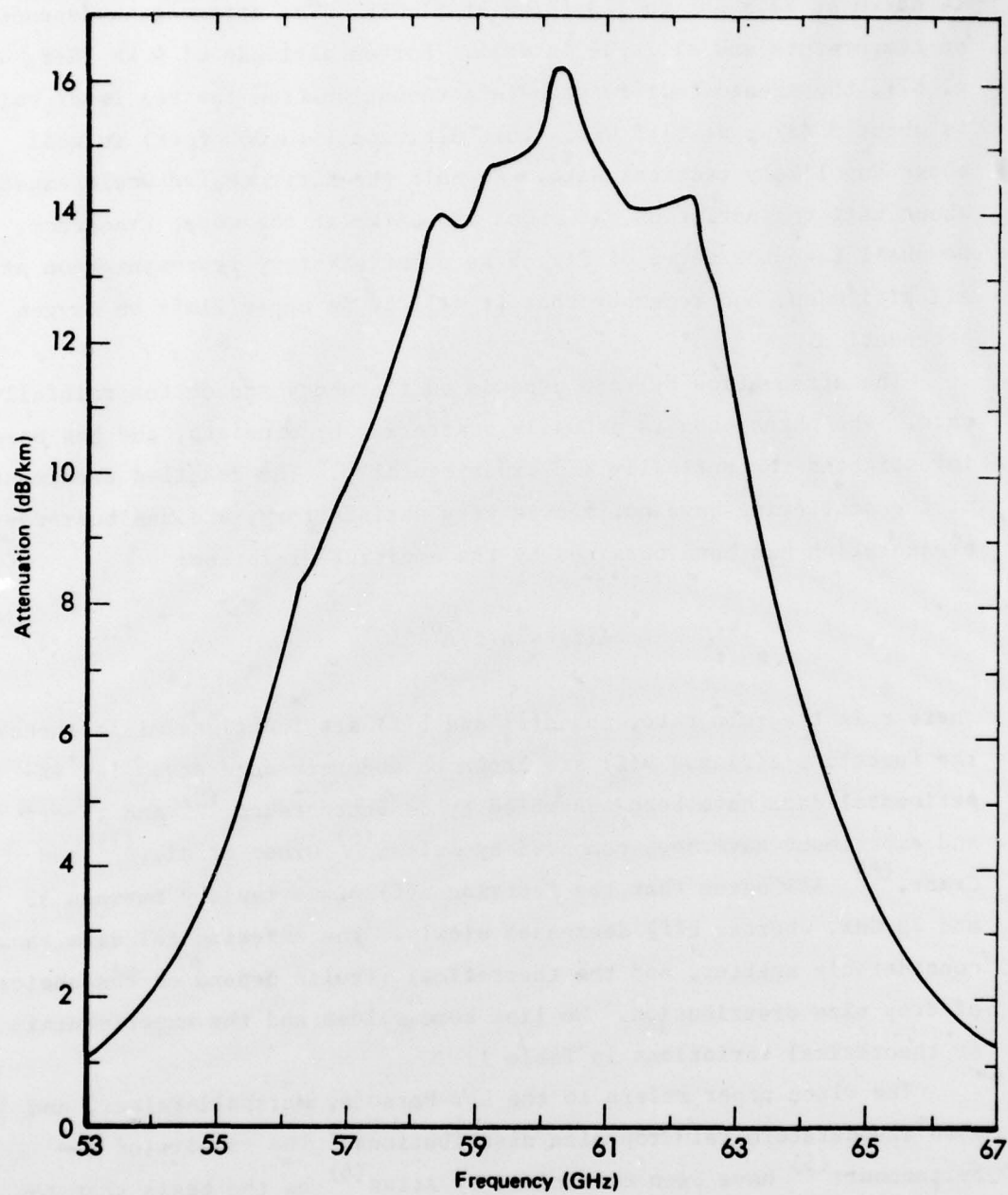


Fig. 9 — Sea level oxygen attenuation

peak attenuation of 16.2 dB/km at 60.3 GHz, then decreases rapidly from 14 dB/km at 62.5 GHz to 1.3 dB/km at 67 GHz. The attenuation depends on temperature and altitude as well. For an altitude of 4 km (Ref. 4, p. 47), the greatest difference in attenuation from the sea level value is about 3 dB/km at 61.8 GHz. This altitude (13,000 feet) is well above any likely tactical path. At half the altitude, we would expect about half the variation, or about 1.5 dB/km at the worst frequency. We shall take the curve of Fig. 9 as a satisfactory representation at all altitudes, and remember that it will be an upper limit on oxygen attenuation.

The attenuation by rain depends on frequency and on the rainfall rate. The phenomenon is actually scattering by droplets, and has been investigated theoretically and experimentally. The detailed treatments of the scattering have not proved very satisfactory, and the best representation has been obtained by the empirical relation:

$$A(f) = a(f)r^{b(f)} \quad (4)$$

where r is the rain rate, and $a(f)$ and $b(f)$ are functions of frequency. The functions $a(f)$ and $b(f)$ are known to moderate accuracy. The experimental data have been assembled by De Bettencourt,⁽⁵⁾ and theory and experiment have been compared by Atlas,⁽⁶⁾ Olsen et al.,⁽⁷⁾ and Crane.⁽⁸⁾ All agree that the function $a(f)$ rises rapidly between 35 and 75 GHz, whereas $b(f)$ decreases slowly. The experimental data show considerable scatter, and the theoretical results depend on the choice of drop size distribution. We list some values and the experimental or theoretical variations in Table 1.

The Olsen paper refers to the Law-Parsons, Marshall-Palmer, and Joss Thunderstorm raindrop size distributions. The results of De Bettencourt⁽⁵⁾ have been criticized by Atlas⁽⁶⁾ on the basis that the experimental data are weighted excessively by a small number of very heavy rains and that, consequently, De Bettencourt's values of $a(f)$ are consistently too high, whereas his values of $b(f)$ are consistently too low. Olsen criticizes the Joss Thunderstorm distribution for precisely the same reason. However, the wide spread in the experimental data

Table 1

FUNCTIONS $a(f)$ AND $b(f)$

Sources of Fitted Curve Points	30 GHz		40 GHz		50 GHz		60 GHz		70 GHz	
	$a(f)$	$b(f)$	$a(f)$	$b(f)$	$a(f)$	$b(f)$	$a(f)$	$b(f)$	$a(f)$	$b(f)$
De Bettencourt:										
Fitted curve	.25	.95	.4	.88	.6	.82	.82	.77	1.1	.73
Data range	.3-.5	.8-1.0	.18-.3	1-1.1					.8-1.3	.65-.78
Atlas	.16	1.05	.30	.98			.64	.87		
Olsen: ^a										
LP drop size	.16	1.06	.31	.98	.49	.91	.66	.85	.80	.81
MP drop size	.19	1.04	.36	.97	.58	.91	.80	.85	1.0	.81
JT drop size	.27	.82	.45	.76	.63	.71	.80	.68	.83	.66
Crane	.16	1.07	.30	1.03	.46	.98	.60	.94	.73	.89
Selected average ^b	.16		.30		.47		.63		.77	

^aLP = Law-Parsons, MP = Marshall-Palmer, and JT = Joss Thunderstorm.^bAverage of Atlas, Olsen LP, and Crane values.

should cause one to pause before using these fitted results with much confidence. In particular, the relatively slight total variation of $b(f)$ over the entire frequency band and the low precision of the values make it reasonable to replace $b(f)$ by a constant for which we have chosen the compromise value 0.95. For the function $a(f)$ we have used the average of the Atlas, Olsen Law-Parsons, and Crane values, as shown in the last row of Table 1.

All the data and analysis refer to point rainfall. If the exponent $b(f)$ were equal to 1, the total rain-induced attenuation along the path would be proportional to the path length and the average rain rate along the path. Since the exponent is nearly equal to 1, we shall use the path average rain rate for calculation, and expect that the error resulting from this approximation will be less than the error in determining the path average.

Light rainfall (less than 2 mm/hr) is generally widespread in character, and the path average is the same as the local value. Heavier rain usually occurs in convective storm cells, which are typically 2 to 6 km across and are often imbedded in larger regions measured in tens of kilometers.⁽⁹⁾ Hence, we expect that for short path lengths (2 to 6 km), the path-averaged rainfall rate will be the same as the local rate, but for longer paths it will be reduced by the ratio of the length of path on which it is raining to the total path length. In any case, the rain rate which should be used with the nomograms is the path-averaged rate.

IV. REDUCTION OF EQUATIONS TO NOMOGRAPHIC FORM

We now discuss how to reduce these relations to the form of nomograms. We employ the techniques of the textbook on graphical presentation by Levens.⁽¹⁰⁾ Equations (3) and (4) and the graph of Fig. 9 are to be displayed.

First consider the range of the variables. From Fig. 9, the attenuation due to oxygen varies up to a maximum of 16.2 dB/km. For the rain attenuation, we use Ref. 8, which contains rainfall statistics for various parts of the world. This reference shows that a rainfall rate of 20 mm/hr would be exceeded only 0.2 percent of the time in the Southeastern United States, and less often in most of the rest of the world excluding the rainier sections of the tropics. Thus, we use a range of 0 to 20 mm/hr for the rain rate, which will cover almost all locations almost all of the time (all but seven hours of the year in the Eastern and Central United States or Europe). At the highest frequency (75 GHz), a rain rate of 20 mm/hr would produce an attenuation near 14 dB/km, so we shall use the same 0 to 16 dB/km scale for rain attenuation as for oxygen attenuation. Thus, the scale for the total attenuation, rain plus oxygen, will go from 0 to 32 dB/km. These scales fit perfectly on standard centimeter graph paper with scale factors of 1 cm/1 dB/km for rain or oxygen separately, 1 cm/2 dB/km for the combined attenuation.

Most tactical communications paths are a few kilometers in length. A 5 km path in the center of the oxygen band at 60.5 GHz has a path loss below 1 km of 78 dB (64 from oxygen, 14 from the inverse square law), which we shall regard as an upper limit, and thus we choose a path loss variation from 0 to 80 dB. This readily matches the other variables with a scale factor of 1 cm/5 dB.

We obtain the relation between frequency and oxygen attenuation directly from Fig. 9 by reading the frequencies at which particular values of attenuation are found. For better accuracy, the original data of Ref. 4 have been employed. This cross-reading provides the information for the left ends of the nomograms, at which the frequency

has been matched to the oxygen attenuation scale. The curious lower end of the frequency scale corresponds to the irregular variation at the top of Fig. 9.

The total attenuation scale is placed midway between the rain and oxygen attenuation scales. A line drawn from a point on the rain scale to a point on the oxygen scale will cross the total attenuation scale at the mean of the two separate ordinates. The extra factor of 2 in the scale factor of the total attenuation line enables the line to show the sum of the rain and oxygen attenuations.

Equation (4), with $b(f)$ set equal to the constant value 0.95, may be displayed by the method of diagonal scales described on p. 384 of Ref. 10. The vertical scales are graduated with the values of attenuation (scale factor $16 \text{ cm}/16 \text{ dB/km} = 1 = m_A$) and $r^{0.95}$ (scale factor $16 \text{ cm}/(20 \text{ mm/hr})^{0.95} = 0.93 = m_r$). The slight departure from linearity in the rain rate scale can be seen by close examination. Let K be the total length of the diagonal scale, where the scale is graduated with the values of a function related to $a(f)$. Draw a line connecting any points on the vertical scales, where the line crosses the diagonal scale at a point labeled f . Let Y_A be this distance along the A scale, Y_r the distance along the r scale, and Y_f the distance along the f scale. The configuration is represented in Fig. 10.

From the similar triangles, we have

$$\frac{Y_r}{Y_A} = \frac{K - Y_f}{Y_f} \quad (5)$$

Solving for Y_f ,

$$Y_f = \frac{K}{1 + (Y_r/Y_A)} \quad (6)$$

With $Y_r = 0.93 r^b$, $Y_A = A$, Eq. (4), this becomes

$$Y_f = \frac{Ka(f)}{a(f) + 0.93} \quad (7)$$

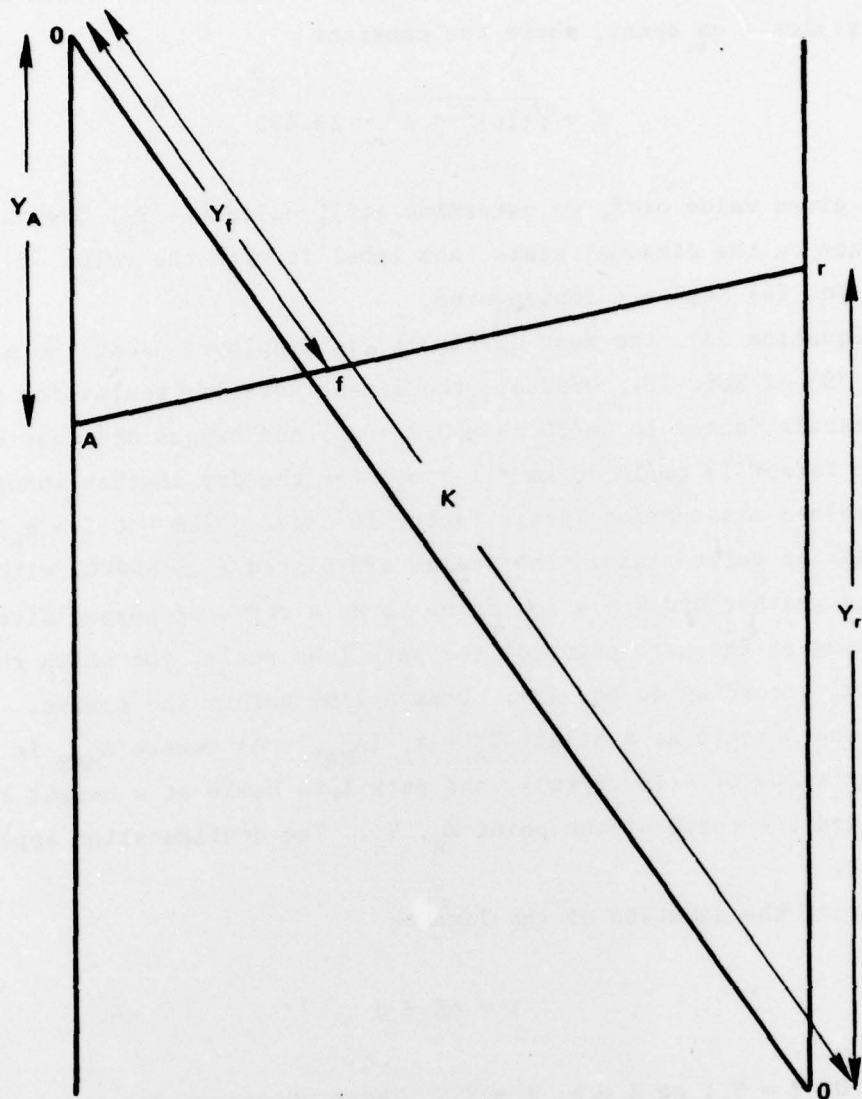


Fig. 10 — Construction for rain attenuation, frequency, and rain rate

For the actual nomograph, we have placed the rain attenuation and rain rate scales 4 cm apart, where the constant

$$K = \sqrt{(16)^2 + 4^2} = 16.492$$

For a given value of f , we determine $a(f)$, calculate Y_f , lay out that distance on the diagonal scale, and label it with the value of f .

Thus, Eq. (4) has been implemented.

Equation (3), the most difficult, is displayed using the method of p. 393 of Ref. 10. Graduate the linear vertical scales for path loss (scale factor 16 cm/80 dB = 0.2 = m_p) and oxygen attenuation (scale factor 16 cm/16 dB/km = 1 = m_A) for the dry weather nomogram, or combined attenuation (scale factor 16 cm/32 dB/km = 0.5 = m_A) for propagation during rain. The scales are placed k cm apart, with $k=10$ for dry weather and $k=4$ for rain. Draw a curve of unspecified shape, beginning at the zero point of the path loss scale, for which the range is 1 km, according to Eq. (3). Draw a line across the scales. It meets the A scale at a height $Y_A = m_A (A_{MAX} - A)$ (where A_{MAX} is the maximum value of A (16 dB/km)), the path loss scale at a height $Y_P = m_p PL$, and the curve at the point X_R, Y_R . The configuration appears in Fig. 11.

Write the equation of the line as

$$Y = cX + d \quad (8)$$

At $X = 0, Y = Y_A$; at $X = k, Y = Y_P$. These relations determine the constants c and d . Since X_R, Y_R is a point on both the curve and the line, they also satisfy Eq. (8), whence:

$$Y_R = (Y_P - Y_A) X_R/k + Y_A \quad (9)$$

Substitute for Y_P and Y_A and solve for PL , obtaining

$$PL = \frac{m_A}{m_p} \left(\frac{k}{X_R} - 1 \right) (A - A_{MAX}) + \frac{k}{m_p} \frac{Y_R}{X_R} \quad (10)$$

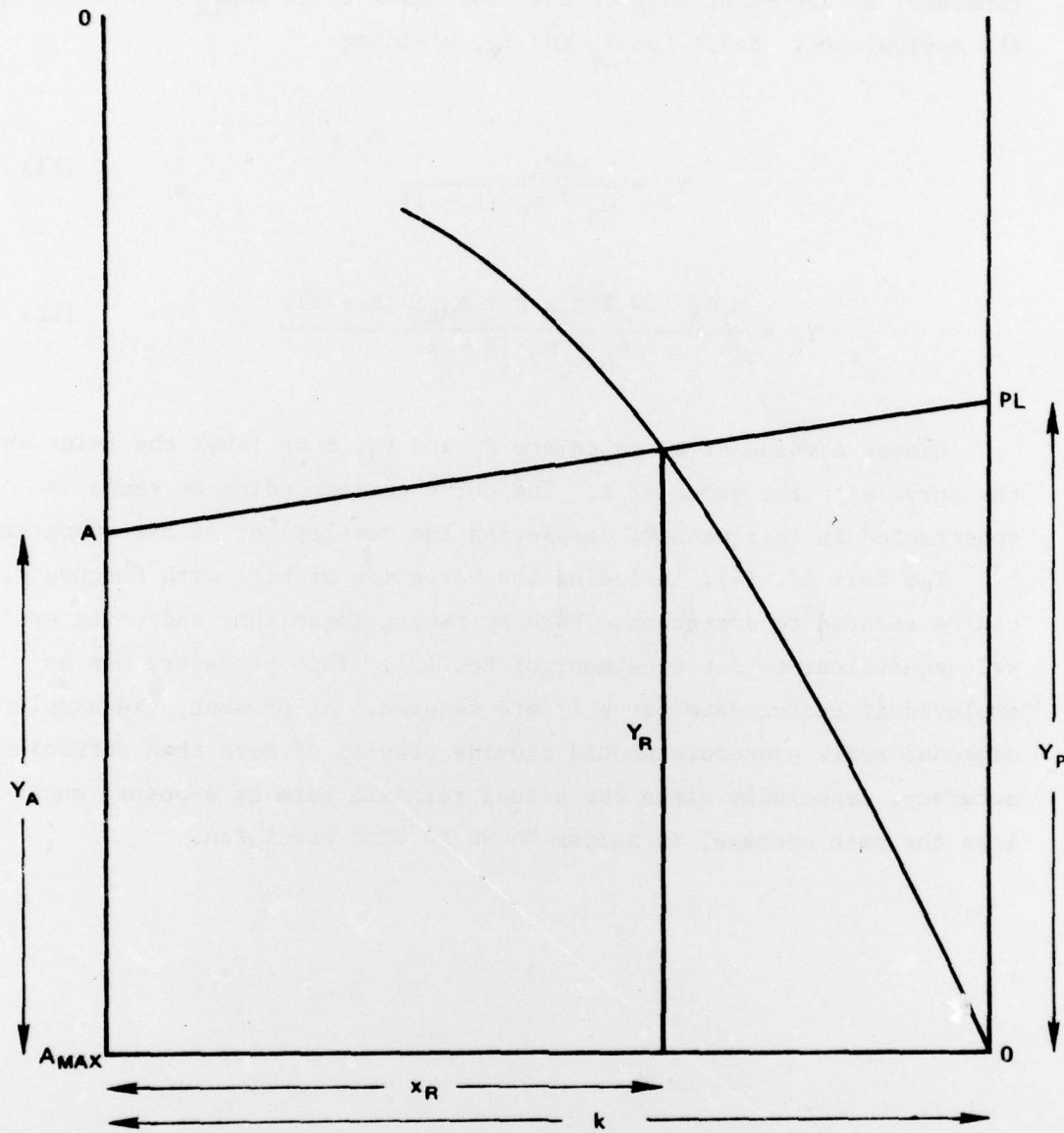


Fig. 11 — Construction for attenuation, range, and path loss

Equate the coefficient of A to $R - 1$ to match Eq. (3), then set the remainder of the right side of Eq. (10) equal to $20 \log_{10} R$ to complete the equivalence. Solve for X_R and Y_R , yielding

$$X_R = \frac{k m_A}{m_A + m_P (R - 1)} \quad (11)$$

$$Y_R = \frac{m_P m_A [20 \log_{10} R + A_{MAX} (R - 1)]}{m_A + m_P (R - 1)} \quad (12)$$

Choose a value of R , calculate X_R and Y_R , then label the point on the curve with the value of R . The curve corresponding to range is constructed in this manner, completing the development of the nomograms.

The full Eq. (4), including the variation of $b(f)$ with frequency, can be reduced to nomographic form by taking logarithms and using analysis equivalent to our treatment of Eq. (3). This procedure can be employed if better data for $b(f)$ are secured. At present, the simpler diagonal scale procedure should provide results of more than sufficient accuracy, especially since the actual rainfall rate at a point, much less the path average, is seldom known to high precision.

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